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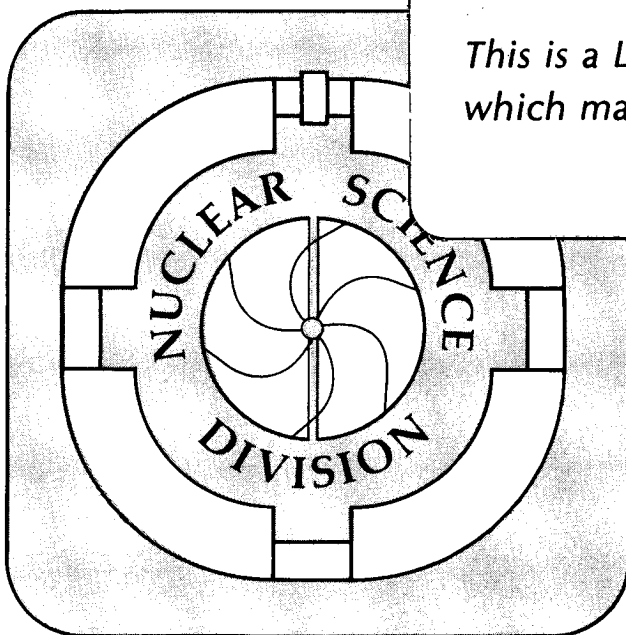## UNIVERSITY OF CALIFORNIA

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A Novel Approach to the Measurement of the Neutron Multiplicity Associated with Reverse Kinematics Heavy Ion Reactions

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Abstract: A new fast neutron high multiplicity detector is proposed based on the measurement of the total light yielded by the neutrons in a plastic scintillator. Its performance is simulated by Monte Carlo methods and compared to existing neutron multiplicity detectors. A cost effective design for reverse kinematics heavy ion reactions is presented and connected problems discussed.

1. Introduction.

The knowledge of the neutron multiplicity associated with nuclear reactions has become increasingly important in intermediate energy heavy ion physics[1] where it can provide a measure of the size of the participant region and the energy dissipation. A large detection efficiency and solid angle of the detector makes the measured neutron multiplicity close to the real one[2]. Under optimum conditions the on line tagging of individual nuclear reaction events may become possible.

So far two main techniques of neutron multiplicity measurements have been developed, the first based on multidetector walls or balls[3,4], the second on the thermalization of the neutrons and the counting of the capture events which are dispersed in time (Gd-doped liquid balls[5]). For high multiplicities of fast neutrons, these techniques suffer from a large cross talk[4,6] between the detectors due to the increased path of multiple scattered neutrons, or from the difficulty of thermalizing high energy neutrons in a resonable volume of scintillating liquid[2,5]. In addition, the Gd balls are very slow because of the thermalization and capture time of about 100 μs.

A cost effective neutron multiplicity technique is presented here, which is particularly adapted to high energy neutrons and higher multiplicities. Its development is beeing designed to carry out measurements[7] on the momentum transfer and energy dissipation associated with the origin of complex fragments emitted in heavy ion reactions.

2. Technique.

The response function of a plastic scintillation detector to a neutron is dispersed up to the maximum light yield of the proton recoils, even if a sufficient depth of scintillating material is provided to allow for slowing down of the incoming neutron. This is due to the different light yields of the various charged prongs originating from the different reactions of the neutron with the organic material, which sum up to a light output strongly depending on the detailed story of the energy deposition. In Fig.1 the response of a 100 cm x 50 cm cylindrical block of

NE 110 plastic scintillator to 10 and 20 MeV neutrons is shown, as simulated by a Monte Carlo (MC) program[8].

Even if this response were to be considered completely flat (and it is not, see Fig. 1), the integral response to a number v_n of monoenergetic neutrons detected at the same time has a mean value equal to v_n times the mean response to a single neutron, and a dispersion approximately $\sqrt{v_n}$ times the dispersion for a single neutron. If the neutron multiplicity v_n is sufficiently high, a reasonably low relative dispersion can be obtained, with a mean response proportional to the multiplicity. Thus, high multiplicities of neutrons of approximately the same energy can be measured through the total light response of a plastic scintillator calorimeter to the neutrons. The requirement of a low neutron energy spread is fulfilled with reverse kinematics reactions where the source velocities can be made much greater than the mean neutron velocity in the source frame.

The MC program of ref.8 has been modified to accumulate the response of many neutron histories and, in addition, to propagate the neutrons also in inert materials, as the ones of the shielding[9]. Calculations have been performed for v_n=30 for the same geometrical configuration and neutron energies of Fig. 1; the resulting response functions, reported in Fig. 2, show dispersions respectively of ±14,5% and ±19%, an acceptable resolution for a multiplicity measurement of ver fast neutrons .

In order to construct a detector based on this "calorimetric" approach, a number of problems must be solved. The problems concern the physical aspects of the nuclear reactions to be studied (solid angle of the neutron emission, energy distribution of the emitted neutrons) and technical peculiarities of the detector (detection efficiency, discrimination from the γ flash, light attenuation in large volume detectors, electronic amplification stability, calibration of the apparatus).

3. Energy Distribution of the Neutrons and Calibration.

From the previous arguments of the last section, the conversion factor between the average detector response and the neutron multiplicity depends on the energy of the neutrons considered. In the ideal case of monoenergetic neutrons, this dependence is shown in Fig. 3 (values are given in Table 1) for three neutron energies, as calculated with the MC program. As can be seen, this dependence is

quite linear. However, if the energy of the neutrons were completely unknown, it would be impossible to obtain the neutron multiplicity from the light output of the "calorimeter".

The energy distributions of the neutrons emitted from the nuclear reactions of interest are mostly maxwellian in form with very minor high energy tails. It is thus reasonable to investigate the effect of a gaussian neutron energy distribution on the total neutron response of the "calorimeter". In Table 2 (case c) the results of this investigation is shown, assuming a FWHM=40% for the gaussian neutron energy distribution. It is evident that the total neutron response is related to the multiplicity as in the case of monoenergetic neutrons with energy equal to the mean value of the distribution (Table 2, case b), while its resolution is degraded only a little. Therefore, only the mean value of the neutron energy distribution is relevant for the absolute calibration of the multiplicity scale, and the resolution of the measurement is not substantially degraded. The mean neutron energy value can be easily calculated[10] or measured by time-of-flight with a small detector or, if a sufficiently long flight base is available, with a module of the "calorimeter" itself, whose structural details are reported below.

The calibration of the light yield can be done, lacking saturation effects, in a neutron generating facility and with the associate particle technique[11] in an event by event recording measurement, by summing in the offline analysis the response to many single monoenergetic neutron to simulate multiple detection events.

4. Solid Angle of Neutron Emission and Detection Efficiecy.

If a neutron multiplicity tagging of individual reaction events is required or, simply, reliable neutron multiplicity distributions are to be recordered, the detection sistem cannot afford a consistent loss of neutrons caused by solid angle or low detection efficiency. In heavy ion reactions, the high energy neutrons emitted are often confined in a forward small cone. This frequently happens in reverse kinematic reactions[7] due to the large c.m. velocities of the emission sources. In these situations an optimum cost to performance ratio can be obtained from the "calorimetric" approach. The following simulations have been done for a 0° apparatus with small transverse dimensions.

A number of calculations with the MC code have been performed to evaluate

the optimum dimensions of the calorimeter for outward multiple scattering, with respect to the area of the neutron impact zone, and to investigate the effect of inert materials added as γ ray shielding. As can be seen from Table 2 (case a and b), 10 cm extra scintillating material is sufficient to give optimum energy deposition. After the addition of γ ray shielding a small degradation of the neutron response resolution is observed, to be optimized with the necessity of limiting the response to γ rays, as discussed below.

The optimum depth of the scintillator has been investigated at several neutron energies and the total neutron response mean values and resolutions at typical neutron multiplicities are reported in Fig. 4 as a function of the scintillator depth. The fractional resolution improves with the depth, approaching a constant value when sufficient depth is provided for maximum energy deposition. It seems that a 50 cm depth is sufficient for up to 20 MeV neutrons, while a 100 cm depth is required for neutron energies up to 50 MeV. In these cases the evaluated resolution are ±19% and ± 25% respectively. In reverse kinematics nuclear reactions, the energy of the ejectiles is strongly coupled to the energy of the c.m. system and the reaction products are strongly forward focused. As the bombarding energy is increased, the neutron energy also increases while the emission angle decreases. A modular design of the "calorimeter" could allow higher energy reverse kinematics reactions to be studied when less solid angle but more depth is required. This feature has been incorporated into the final design.

5. Discrimination Against the γ ray Flash.

Organic scintillators are also sensitive to γ rays which yield more light than neutrons for equal energy deposition[12]. It is therefore essential to separate the amount of light generated by neutrons from the light generated by γ rays in the "calorimeter". The method to be employed takes advantage from the different time-of-flight between neutrons and γ rays. The scintillation light yielded by the event will be integrated with increasingly delayed gates. From the multiple record, the function of the light yield vs time will be differentiated and the residual tail from the prompt γ flash subtracted by fitting typical flash shapes.

The success of this procedure is certain only if, at the time of arrival of the neutrons, the prompt γ ray flash has decayed enought so that it does not greatly

contaminate the delayed neutron signal. Due to the limited decay time (tens of nsec) allowed by the short flight needed to maximize the solid angle (a few meters), care must be taken to limit the absolute number of the prompt γ rays entering the "calorimeter". A lead shielding of 2 mm thickness has good absorbtion capability for γ rays of up to hundreds of keV, which constitute the bulk of prompt emission[13], without a significant loss in the resolution of the multiplicity measurement. The adopted shielding is furthermore well suited to absorb all the fast light charged particles penetrating the reaction chamber walls. Extending the lead shielding over all the calorimeter helps reduce the background due to area activation. The phototube thermal noise contributes little on the average to the total response.

6. Light Attenuation and Electronic Stability.

The collection of scintillation light can suffer some attenuation for the events flashing far from the photomultiplier[14,15]. The difference between the light collected from near and far flashing events is greatly reduced[16] taking advantage of total internal reflection in slabs of a good transmission scintillating material (for instance NE 110 from Nuclear Enterprises - Edinburgh - U.K.), not too long with respect to the attenuation lenght (almost 4 m for NE 110[16]) . With all these conditions the differences in light collection are expected to be within the scintillator resolution[17] (a few percent) and not to contribute appreciably to the overall response resolution.

The requirements for a good uniformity of light collection from the scintillator lead to a modular design of the "calorimeter". This choice is also in accordance with the solid angle-depth inverse correlation (see end of sect. 4). Taking into account the energy spectra of neutron emission in intermediate energy heavy ion reactions[18], the efficiency at various depths presented in sect. 4 and the industrial availability of scintillator thicknesses, the optimum dimensions for the modulus of the calorimeter are (60 x 50 x 25)cm^3 with light collection from the smallest side.

The electronics will contribute very little to the overall resolution. The same can be said of the gain drifts of the photomultiplier tubes, with a careful periodical testing procedure.

7. A Proposal for the Modular "Calorimeter".

The dimensions of the module presented in the last section allow for the mounting of 16 units as in Fig. 5a with a total depth of 50 cm, for neutron energies up to about 20 MeV, or as in Fig. 5b with a total depth of 100 cm, for larger energies. The hole for the beam line represents about 6% of the total area of the device in the "low energy configuration" of Fig. 5a and 1% in the high energy configuration of Fig.5b. This hole has very little influence on the actual value of the average light response, if substantial neutron loss by statistical effects (low multiplicity case) can be discarded. Furthermore, the loss of resolution is not significant being of the percent level as compared with the overall resolution values already shown.

The hollow central volume not occupied by the beam line pipe can be heavily shielded by lead to reduce any stray radiation. The addition of lead in this central part plays also a small, but positive role in recovering some energy deposition in the scintillators by multiple scattering of the central neutrons otherwise lost.

8. Conclusions and Comments.

In this work an alternative approach has been presented to the measurement of high multiplicities of very fast neutrons. The results which can be obtained compare favourably with different methods already developed for neutron multiplicity measurement in a smaller neutron energy range and which are not very good for higher neutron energies.

An apparatus has been proposed which is flexible in optimizing its performance in relation to the physical properties of the nuclear reactions in interest. The costs of such an instrument are modest (S 13,000 for scintillator, light guide, photomultiplier, base and high voltage power supply of a modulus).

9. Acknowledgment

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Figure captions

Fig.1 MonteCarlo simulation for the response function of a cylindrical 100 cm x 50 cm NE110 plastic scintillator to 10 and 20 MeV neutrons uniformly impinging on the central part of the base (40 cm radius).

Fig.2 Calculated response function of the apparatus of Fig. 1 to a neutron multiplicity $v_n=30$ at neutron energies of 10 MeV (full-line histogram) and 20 MeV (dashed-line histogram).The curves are gaussian fits with FWHM of 29% (full line) and 38% (dashed line).

Fig.3 Average response (in MeV electron equivalent units) of the apparatus of Fig.1 evaluated vs neutron multiplicity for monoenergetic neutrons of 5 MeV (open square), 10 MeV (open circle), and 20 MeV (open triangle). The reported error bars represent the FWHM of the gaussian fits to the total response, as in Fig.2.

Fig.4 Calculated response (MeVee) and dispersion vs scintillator depth. The base of the scintillator has a diameter of 100 cm and the neutrons impinge on the central part of the base (40 cm radius). A gaussian distribution is assumed for the impinging neutron energy with FWHM of 40% of the mean value. Neutron multiplicity is $v_n=20$.

Fig.5 Layuot of the calorimeter : a) low neutron energy configuration ($E_n<20$ MeV); b) high neutron energy configuration (20 MeV$< E_n <50$ MeV)

Table captions

Table 1 The mean values and resolutions reported in Fig. **1**, of the calorimeter response function versus neutron multiplicity at three neutron energies.

Table 2 Mean values and resolutions of the response function to a neutron multiplicity v_n=30, expected from different devices and conditions: **a)** 10 MeV monoenergetic neutrons uniformly impinging on the calorimeter (50 cm radius) of Fig. 1; **b)** 10 MeV monoenergetic neutrons uniformly impinging on the central part (40 cm radius) of the same calorimeter; **c)** neutrons with a gaussian energy distribution (mean value 10 MeV, FWHM = 4 MeV) impinging as in b); **d)** 10 MeV neutrons in a liquid ball of 50 cm radius (ref. 5).
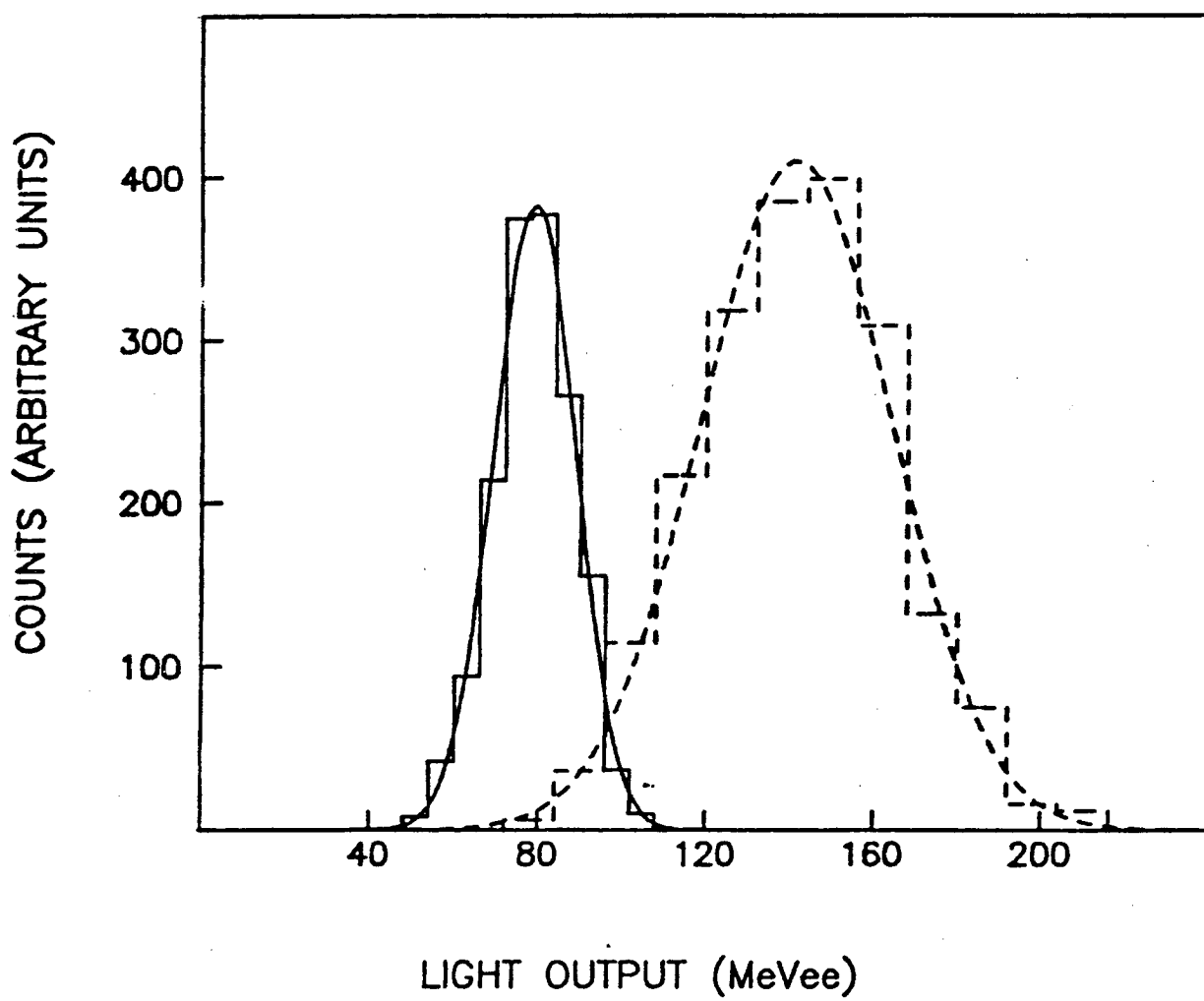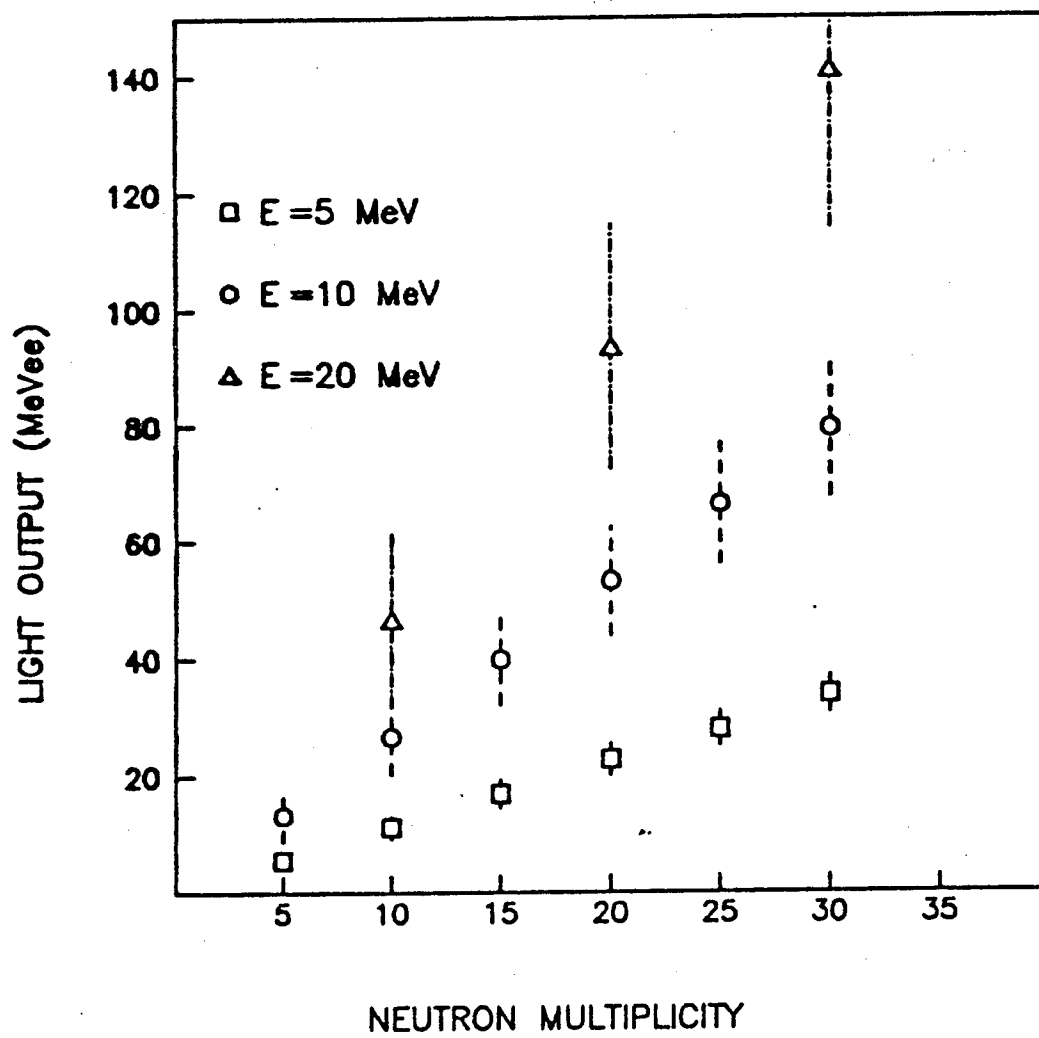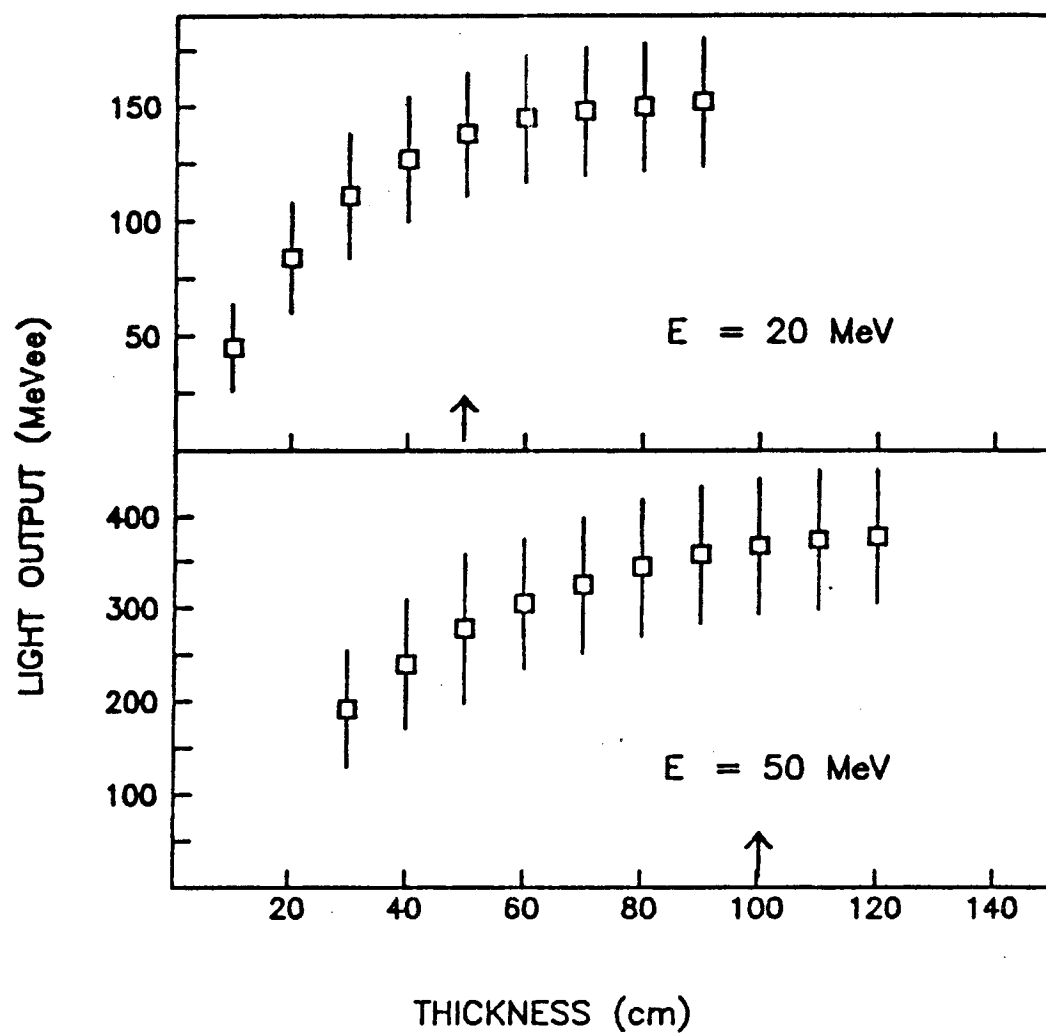
Fig. 1

Fig. 2

Fig. 3

LIGHT OUTPUT (MeVee)

THICKNESS (cm)

E = 20 MeV

E = 50 MeV
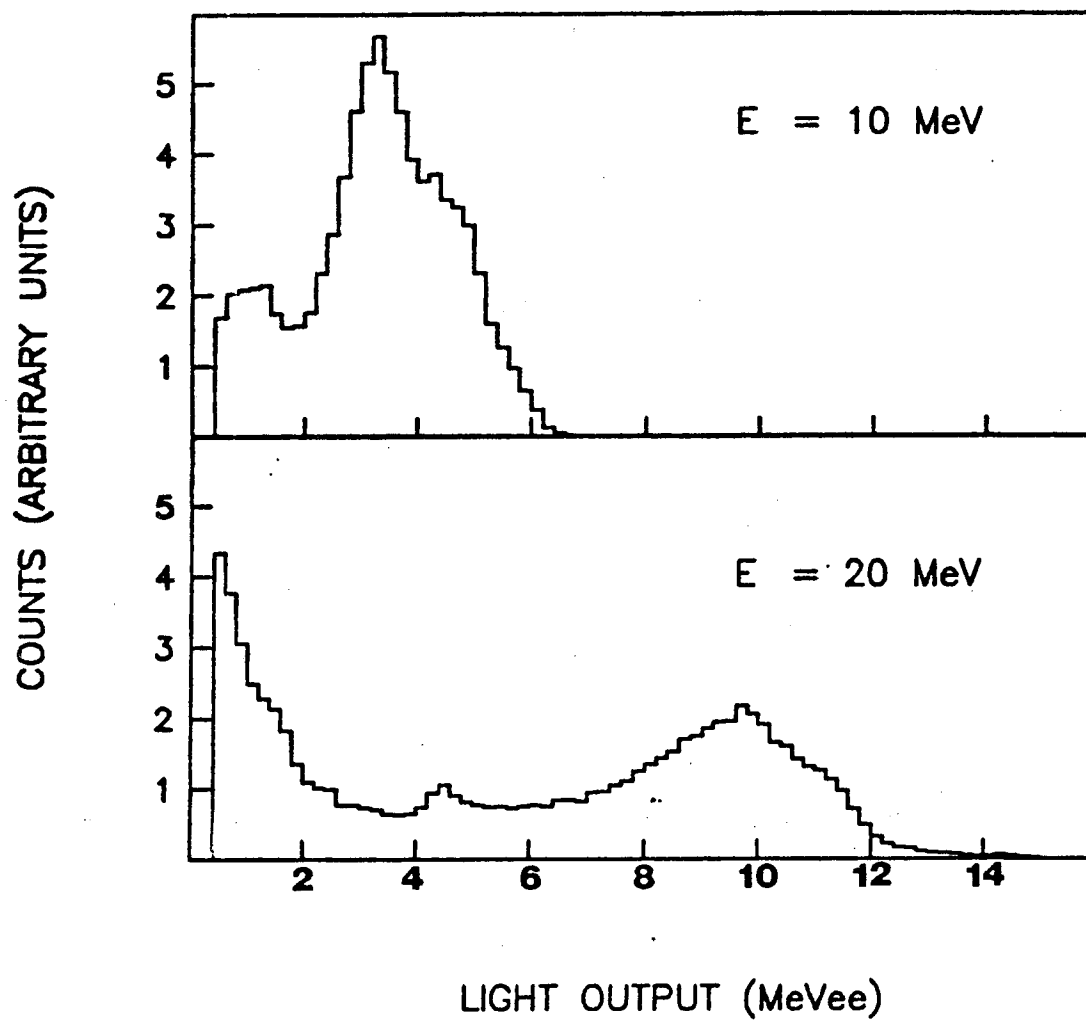
Fig. 4

a) low neutron energy configuration

160 cm

50 cm

b) high neutron energy configuration

110 cm

100 cm
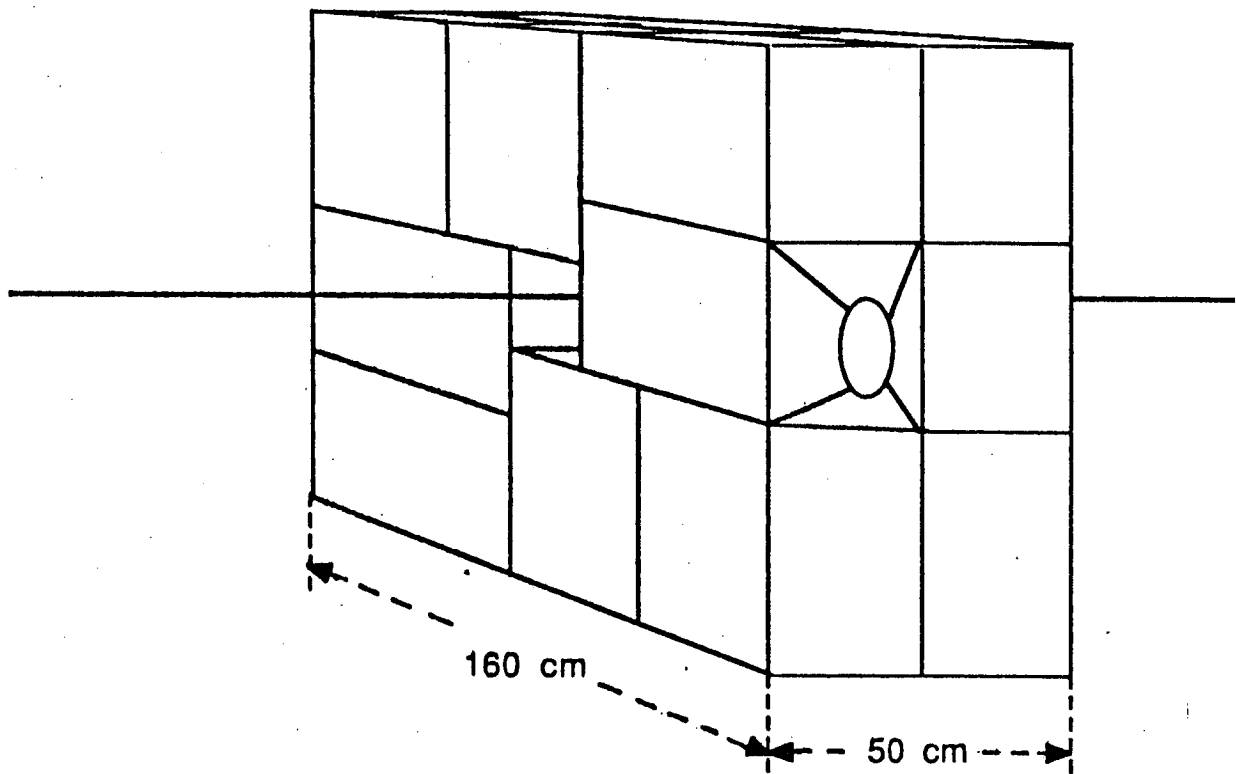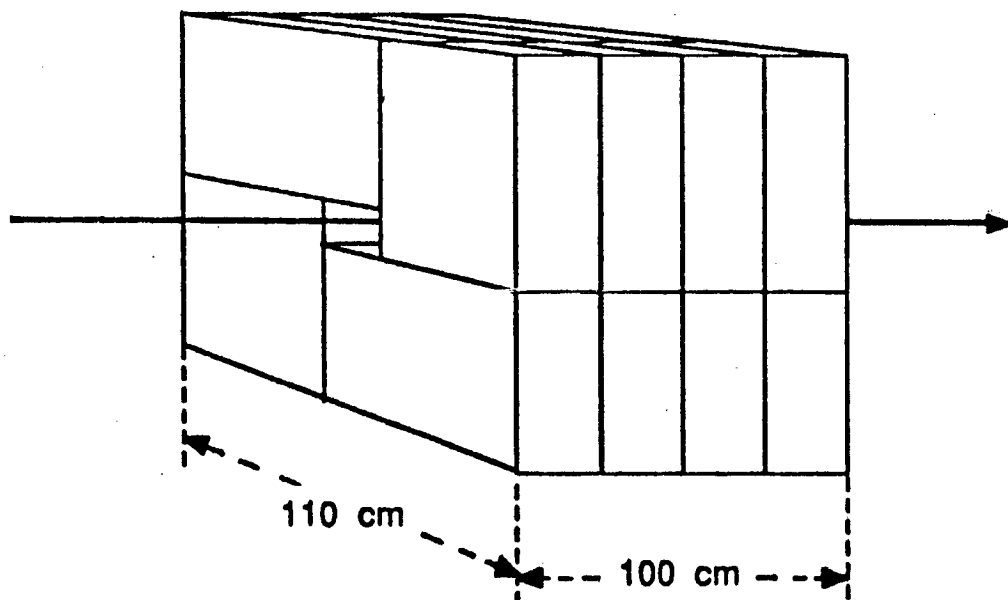
Fig. 5

TABLE 1

ν_n \ LO	5 MeV	10 MeV	20 MeV
5	5.6 ± 1.3	13.3 ± 4.4	
10	11.2 ± 2.0	26.7 ± 6.4	46.8 ± 15.2
15	17.0 ± 2.4	39.9 ± 7.7	
20	22.8 ± 2.7	53.2 ± 9.3	93.6 ± 21.1
25	28.0 ± 2.9	66.5 ± 10.4	
30	33.9 ± 3.1	79.5 ± 11.7	141.0 ± 27.0

TABLE 2

case	expected response	% res.
a)	74.5 ±11.5 (MeVee)	±15.4
b)	79. ±11.5 (MeVee)	±14.6
c)	80. ±13. (MeVee)	±16.2
d)	18.6 ± 2.7 (counts)	±14.5